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A BLUMLEIN MODULATOR FOR A TIME-VARYING LOAD.(U)

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A BLUMLEIN MODULATOR FOR A TIME-VARYING LOAD

Sol Schneider
William H. Wright, Jr.
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Electronics Technology & Devices Laboratory

October 1976

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A modulator has been built to drive a time-varying-impedance load. A Blumlein circuit, with two identical pulse-forming networks, was used to produce an effective voltage of twice the charging voltage. A dissipative clamper circuit was included to simulate a well-behaved load. The switch is a 10 section iterative cavity-grid thyratron designed for 250 kilovolts (kV) and 20 kiloamperes (kA) peak current. The modulator has been operated at 210 kV at a repetition rate of a few hertz (Hz).

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FIGURES

A BLUMLEIN MODULATOR FOR A TIME-VARYING LOAD

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Summary. The Blumlein circuit uses two identical charged PFN's and a switch to short across one PFN to invert it. After inversion, the two PFN's and the load are in series with an effective loop voltage twice the charging voltage. With a mismatched load there are multiple reflections through the PFN's, the switch, and the load. In the present application, the time-varying load (a ramp current in response to a constant voltage pulse) is inherently mismatched. A dissipative clamper circuit was devised which, when connected in parallel with the load, draws a decreasing ramp current. The sum of the clamper and load currents approximates a constant amplitude pulse, and the parallel connection approximates a constant impedance which can be matched to the modulator impedance. Protective circuits included are a clipper diode across the thyratron and an end-of-line clipper circuit to dissipate the stored energy in the event of a load arc. The thyratron used is a 10 section iterative cavity grid tube designed for 250 kV and 20 kVA peak current. Two such modulators have been built. One is at ECOM with a 2.5 μs pulse length, resistive load, and a megawatt of average power available. The other is at MICOM with 5 μs, time-varying E-Beam gun load, and to date only single shot operation. Both have operated at 210 kV single shot, and the one at ECOM at 175 kV and 10 Hz.

INTRODUCTION

The drive requirements for a cold cathode electron beam gun of current interest in high energy pulsed lasers are a flat 250 kV, 5 μs pulse with a rising ramp current of 10000 amperes at a pulse repetition rate of 50 Hz. Consideration of the problems in designing switches, charging chokes, power supplies, and pulse transformers for this requirement led to the decision to build a transformerless modulator using a Blumlein circuit and developing a 250 kV switch.

DISCUSSION

E-Beam Modulator Circuit

The Blumlein circuit is the two network case of a Darlington circuit. A schematic diagram of the circuit is shown in Figure 1. The circuit works in the following manner. The thyratron short circuits the front end of the network on the left. This is equivalent to reversing the potential of this network, thus putting it in series with the network on the right. If the gun has an impedance equal to the series rearrangement of the networks, voltage equal to the original dc charging voltage appears across the gun. The reversal process results in a fixed time delay equal to half the pulse width between the firing of the switch and the application of voltage to the gun.

The charging diode, the front end clipper, and the end-of-line clipper are primarily for protective purposes. The charging diode serves a double function. Since the network on the right is isolated from ground, it provides a charging path for this network. In addition, it acts as a clipper diode for the E-Beam gun, removing any inverse voltage that may appear across the load caused by mismatches between the gun and the network. The front-end clipper serves the

same function for the thyratron. Excess inverse voltage on the thyratron may cause it to fire in the inverse direction thus limiting its ability to deionize before application of recharge voltage. The end-of-line clipper with its matching resistor of 12.5 ohms is required in the event of a gun fault. If a gun fault occurs the circuit essentially behaves as a conventional line type modulator with twice the pulse length and zero load impedance. Full inverse voltage appears at the back end of the network on the right. The end-of-line clipper with its resistance matched to the network acts as a load, dissipates the energy and removes the inverse voltage, permitting the modulator to act normally on the next pulse providing the fault in the gun has cleared.

Since the gun has a variable impedance with its resistance varying from essentially infinity at the beginning of the pulse to the effective network impedance of 25 ohms at the end of the pulse, the positive mismatch at the beginning of the pulse causes the full voltage of the networks in series, 500 kV, to appear on the gun causing it to arc. Therefore a clamper circuit is required to limit the voltage. The conventional clamper circuit consists of a large capacitor charged to the operating voltage of the load with a diode in series to prevent discharge into the load. The size of the capacitance is determined by the degree of variability in the load and the percentage regulation required. Since the specific gun uses only half the available charge, approximately half of the 10000 joules stored in the network would have to be diverted to the clamper capacitor. In addition, the voltage on the gun is not to rise more than 10 percent during the pulse. Therefore the additional 5000 joules on the clamper capacitor should not raise the voltage beyond 275 kV. The minimum size capacitor is 0.76 μF and stores 29000 joules at the maximum voltage. If the negative end of the gun is grounded the power supply filter bank could be used as the clamper capacitor with the energy conserved. Since the positive

side of the gun is grounded, the clamper circuit is now the opposite polarity and a separate capacitor bank and a 250 kV power supply are required. In addition, a bleeder resistor across the clamper capacitor is required to discharge the capacitor back to 250 kV between pulses. A potential problem could occur if the clamper diode were to short and the stored energy dissipated in the gun.

Considering the problem in the use of a conventional clamper circuit, a clamper circuit was devised to eliminate the need for large energy storage and an additional power supply. The basis for the new circuit is that the parallel combination of the E-beam gun and the clamper circuit should effectively appear as a constant 25 ohm load impedance to the modulator. The circuit devised is shown on the diagram. It consists of a capacitor in series with a 25 ohm resistor and diode with a bleeder resistor across the capacitor. When the initial voltage pulse appears across the combined load it sees a 25 ohm impedance. The gun dissipates only half of the stored 10000 joules in the network. Since about half of the diverted energy is dissipated by the series resistor in charging the clamper capacitor the size of the clamper capacitor is chosen to charge to 250 kV with the remaining energy. The size of the required clamper capacitor is reduced to 0.08 μF, one-tenth of the size of capacitor required in a conventional clamper circuit. The bleeder resistor must now during the interpulse interval, dissipate the 2500 joules stored in the capacitor. The time constant of the bleeder resistor in combination with the clamper capacitor must be less than one-fifth the interpulse interval. This clamper circuit permits single-shot operation, varying repetition rates, eliminates the additional power supply and reduces the danger if the clamper diode shorts because of the low energy storage and the series resistor.

The Blumlein circuit and the clamper circuit were tested in a low voltage circuit at 5000 volts. Figure 2 shows the results. In this circuit a Blumlein circuit consisting of two 45 ohm, 2 μs networks and an L-R load to simulate the gun characteristic were used. The clamper circuit consisted of an 0.02 μF capacitor in series with an 88 ohm resistor and a 58000 ohm bleeder resistor in parallel with the capacitor. Figure 2 (a) shows the waveforms without a clamper. The initial voltage on the load is nearly doubled and various voltages, both positive and negative, appear across the load after the main pulse. Also an additional current pulse appears in the thyratron circuit. Figure 2 (b) shows the effect of the clamper circuit. The load voltage is constant and the various voltage excursions after the pulse disappear. The slow decay in load current at the end of the pulse is due to the inductance used to simulate the time varying gun impedance. The I-t characteristic of the actual E-Beam gun load is shown in Figure 3, increasing approximately linearly for 3.5 μs and slowly thereafter. The gun impedance at the knee is 17.0 ohms.

Two full-scale modulators at 250 kV have been built and will be described later. Because of malfunctions in the clamper and EOL clipper diodes, additional simulation was done to determine the transients during load-open (gun not conducting) and load-short conditions. This was done at 100 volts with two 5 μs, 25 ohm PFN's and a microswitch in place of the thyratron. The circuit has a matched EOL clipper, charging diode, and clamper circuit. The load resistor was omitted to simulate a non-firing gun, but the normal operation waveforms, Figure 4, were obtained by shorting the clamper capacitor, C_c, using the clamper resistor as a dummy load. The values of the clamper components, R_c and C_c, were chosen so that R_c equalled the sum of the characteristic impedances of the PFN's, 50 ohms, and C_c 0.05 μF, equalled 1/4 the total PFN capacitance.

The factor of 1/4 comes from the fact that with a linear ramp current and constant voltage, 1/2 the stored energy goes into the load and 1/2 into the clamper circuit. One-half the clamper energy goes into the clamper resistor, R_s, the rest is stored in the clamper capacitor to be bled off in the interpulse interval. In practice, the size of C_c will be adjusted for the best pulse shapes and least reflections throughout the circuit. As C_c is decreased the amplitude of the voltages in the clamper circuit increases, and Figure 5 shows the waveforms for C_c = 0.05 and C_c = 0.025 μF. To have flexibility in varying the clamper circuit for best matching, the clamper components must be chosen conservatively. With C_c = 0.025 μF, the clamper voltage goes to 165 percent of the dc charging voltage. For other load current pulse shapes, more complex clamper circuits, or even multiple paralleled clamper circuits, with R's, L's, C's, PFN's, and initial bias could be used. If the gun or load shorts at the beginning of the load pulse, the switch current pulse is its normal amplitude and double its normal length, and both PFN's invert, forward biasing the EOL diode and driving a double length current pulse through the EOL resistor, as in Figure 6. The EOL resistance is half that of the load resistor because, with both PFN's inverted, the PFN's are in cascade rather than in series as they are in normal operation. With an open load and C_c = 0.025 μF, Figure 7, the EOL diode voltage rises 26 percent over the charging voltage, but there is no current in the EOL circuit. An SCR across the clamper, which could be triggered at various times with respect to the switch current, was used to simulate a gun short at some time during the load pulse with the load open and the load voltage higher than normal.

Figure 8 shows the clipper diode voltage and current when the open load is shorted near the end of the load pulse; Figure 9 is an expansion in amplitude and time showing oscillations which are shock excited by the high di/dt in the clamper circuit. Figure 10 shows the difference in clipper diode current for a fast- and slow-recovery diode. The high frequency ringing is 3.5 times less with the fast diode.

The effect of a short after part of the load voltage pulse into an open is shown in Figure 11, along with the difference between a slow-and-fast-recovery clamper diode. The slow diode contains more stored charge which must be swept out by reverse current before conduction stops. The very large dV/dt across the clmaper diode, even though in the direction of decreasing voltage, and the fast ringing in the clipper diode, together with the lack of R-C compensation may account for the diode failures. The replacement diodes will be compensated.

Two similar Blumlein modulators have been built to operate at 250 kV. One, at ECOM, shown in Figure 12, uses two 12.5 ohm,2.5μs PFN's, energy storage of 5000 joules, a resistive load, no end-of-line clipper, no clamper circuit, and no charging diode. This modulator is used for developing the iterative cavity-grid thyratrons and has a megawatt of average power available - 4 amperes at 250 kV. The other at MICOM, has two 12.5 ohm 5 μs PFN's, clamper, EOL clipper, charging diode, and the cold cathode electron beam gun load. To date, only single shot testing has been done on this modulator because of power supply limitations. The series resistor in the clamper circuit can be connected as a dummy load for testing. All resistors used are copper sulfate-sulfuric acid-water electrolytes in glass pipes and are cooled by circulating through heat exchangers. The EOL resistor, because its use is intermittent, is uncooled. The switch in both modulators is a 10-gap iterative cavity-grid

deuterium thyratron built by EG&G. The tube development is not yet complete, especially with regard to grid baffling and external voltage-division circuits, but both modulators have operated up to 210 kV single shot and the one at ECOM at 175 kV at 10 Hz. The thyratrons and voltage dividers in both modulators are enclosed in plastic boxes to enable surrounding these components with a high-dielectric-strength gas. Figure 13 is an 8-gap version of the thyratron with a graphical cutaway showing the inner structure. Figure 14 is another view of the same tube.

After running the MICOM modulator for several thousand shots into a resistive load at voltages between 100 and 210 kV, the E-Beam gun load was connected to the modulator with four coax cables, each 50 feet long. The gun was pulsed between 150 and 200 kV for several hundred shots, after which it stopped drawing current, probably because of the clean-up of the light oxide layers which acted as electron sources during the start of gun conduction. A circuit change by Dezenberg at MICOM separating the clamper from the gun with coax cable delayed the clamping effect by 100 ns, putting a voltage spike on the gun to act as a "tickler" and draw electrons from the gun electrodes by field emission. With this change the gun fired satisfactorily, but the diodes had already been heavily damaged.

In addition to clamper and EOL clipper repair, the gun impedance is 17.0 ohms, which presents a basic mismatch to the 25 ohm Blumlein impedance for which the clamper can't compensate. Either the gun impedance will be increased by changing the electrode spacings, or the PFN impedance will be decreased by decreasing inductance.

CONCLUSIONS

A passive, dissipative clamper circuit can improve the matching and reduce transients caused by a time-varying load. Although applicable to any type of modulator, it has been demonstrated here with a Blumlein circuit. When using a load which occasionally may not conduct, such as a field emission E-Beam gun, safety factors must be included when choosing the clamper and clipper diodes, particularly if flexibility is desired in the clamper circuit to optimize waveforms. For the conditions used in the simulation, the clamper capacitor one-eighth the PFN capacitance and shorting the load near the end of the load voltage pulse with the load open, the clamper voltage was 165 percent and the clipper voltage 126 percent of the dc charging voltage. The large dV/dt and ringing currents indicated that R-C compensated diodes should be used.

If it is unlikely that the load will not conduct, the load fault during the pulse is less severe and the safety factors can be reduced accordingly.

ACKNOWLEDGEMENTS

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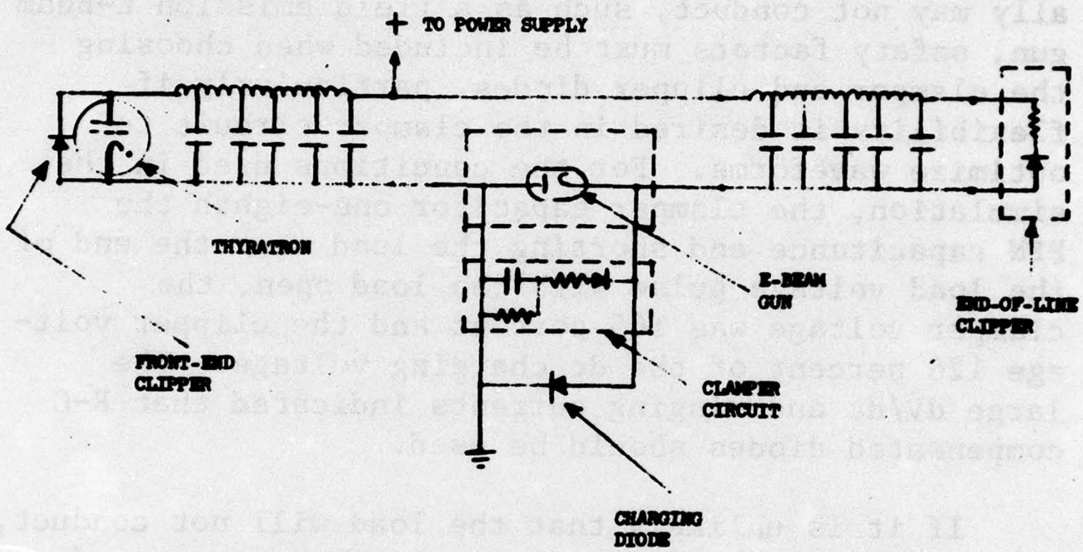


Figure 1, Schematic Of Blumlein Modulator

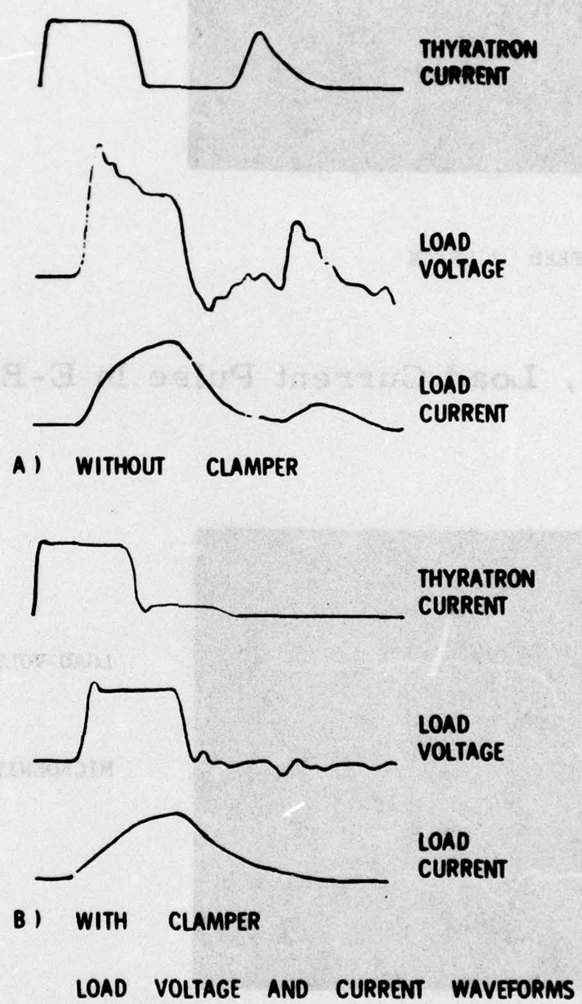
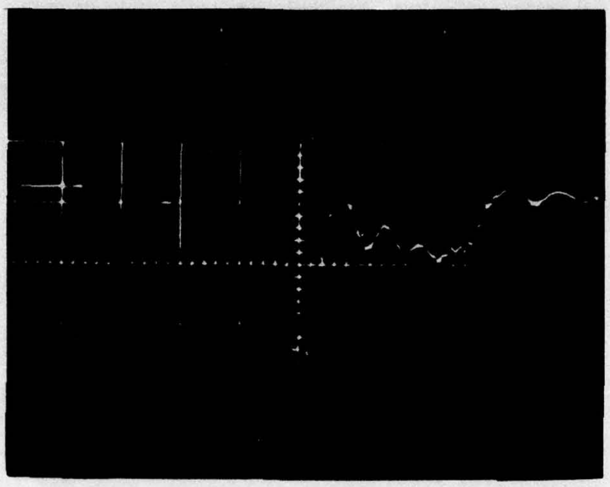


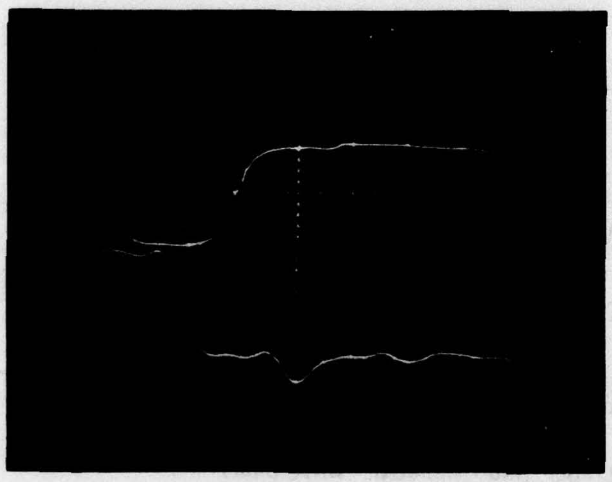
Figure 2, Effect of Clamper Circuit on Modulator Waveforms - Blumlein Simulation



E-BEAM GUN CURRENT 4000 A/CM

SWEEP SPEED 2 US/CM

Figure 3, Load Current Pulse In E-Beam Gun

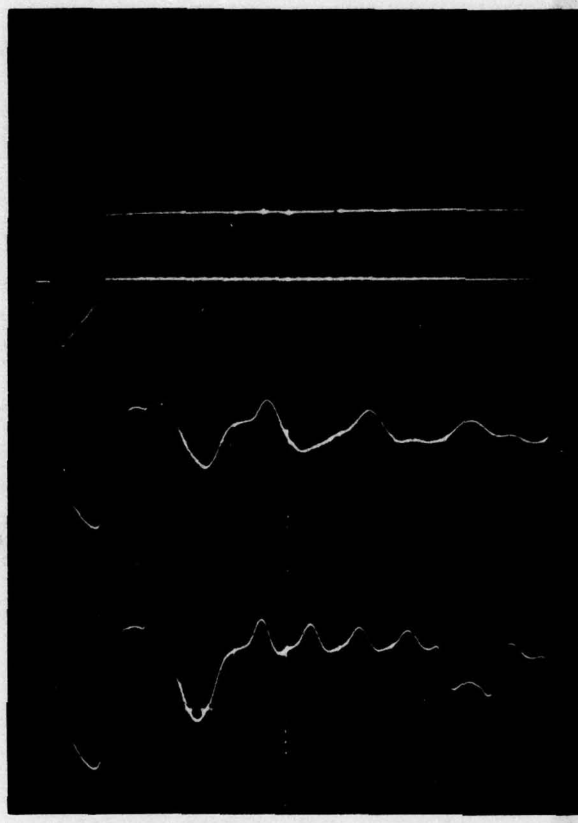


LOAD VOLTAGE, 50 V/CM

MICROSWITCH CURRENT, 2 A/CM

SWEEP SPEED, 2 US/CM

Figure 4, Blumlein Simulation Circuit, Normal Waveforms



CLAMPER CAPACITOR VOLTAGE, 50 V/CM

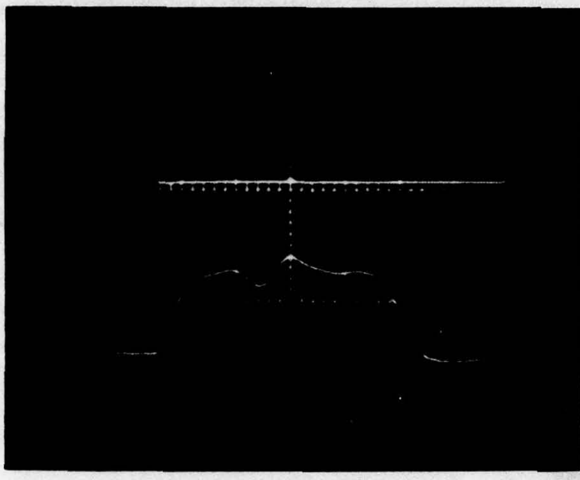
CLAMPER CURRENT

CLAMPER VOLTAGE, 50 V/CM
0.05 UF CAPACITOR

CLAMPER VOLTAGE, 50 V/CM
0.025 UF CAPACITOR

SWEEP SPEED, 5 US/CM

Figure 5, Clamper Circuit Waveforms, Open Load

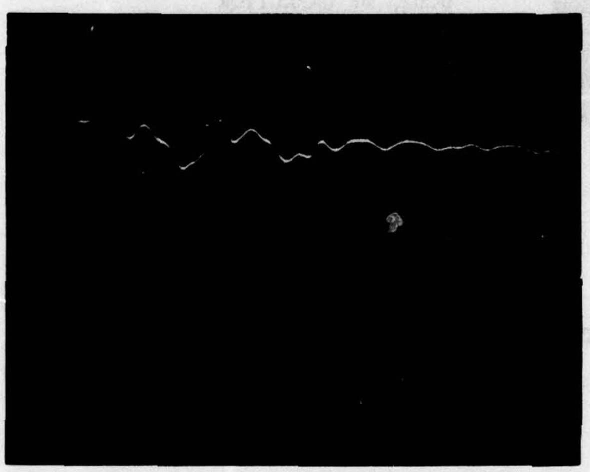


CLIPPER DIODE VOLTAGE, 50 V/CM

CLIPPER CURRENT

SWEEP SPEED 2 US/CM

Figure 6, End-Of-Line Clipper Waveforms, Load Shorted



CLIPPER DIODE VOLTAGE, 50 V/CM

CLIPPER CURRENT

SWEEP SPEED 5 US/CM

Figure 7, End-Of-Line Clipper Waveforms, Open Load

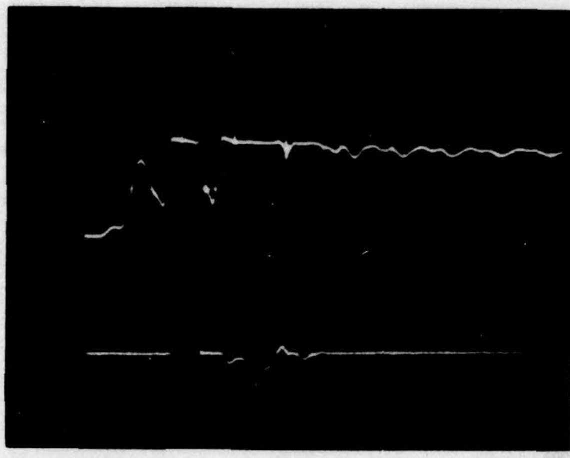


Figure 8, End-Of-Line Clipper Waveforms, Load Initially Open, Shorted Near End Of Pulse

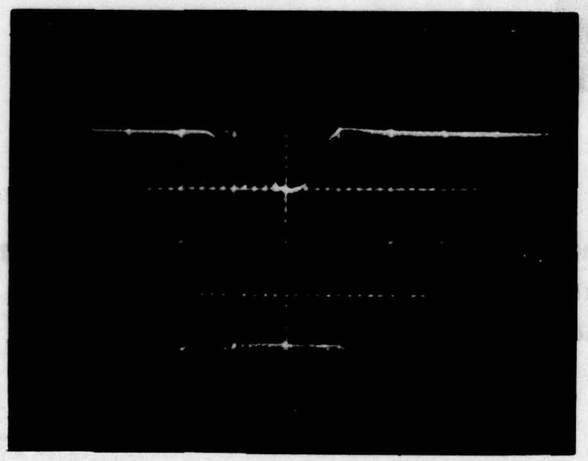
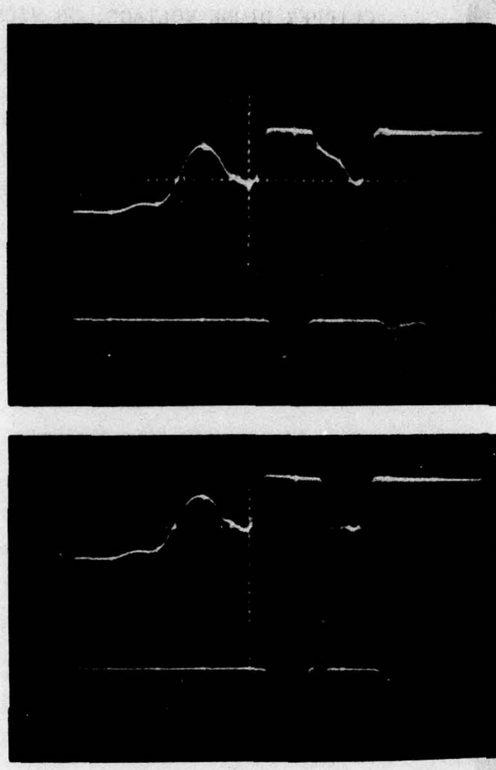


Figure 9, Oscillations In End-Of-Line Clipper, Load Initially Open, Shorted Near End Of Pulse



FAST CLAMPER DIODE

SLOW CLAMPER DIODE

SWEEP SPEED 2 US/CM

Figure 10, Effect Of Clamper Diode Recovery Time On EOL Clipper Waveforms, Load Initially Open, Shorted Near End Of Pulse

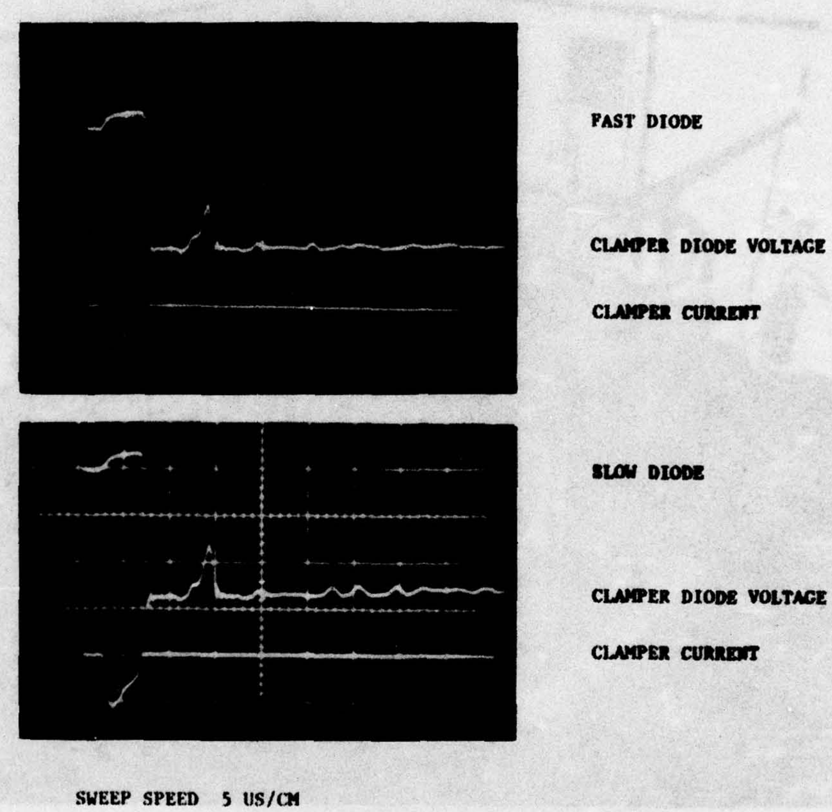


Figure 11, Effect Of Clamper Diode Recovery Time On Clamper Waveforms, Load Initially Open, Shorted Near End Of Pulse

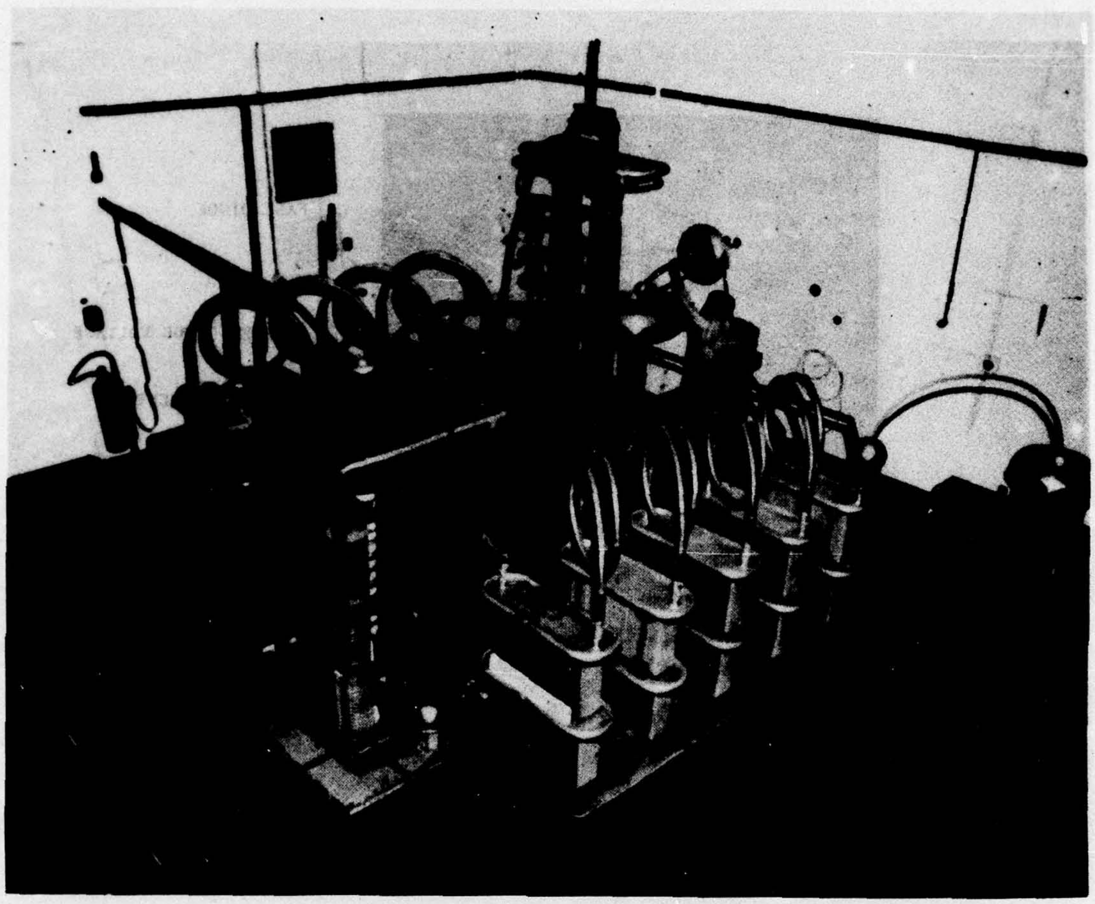
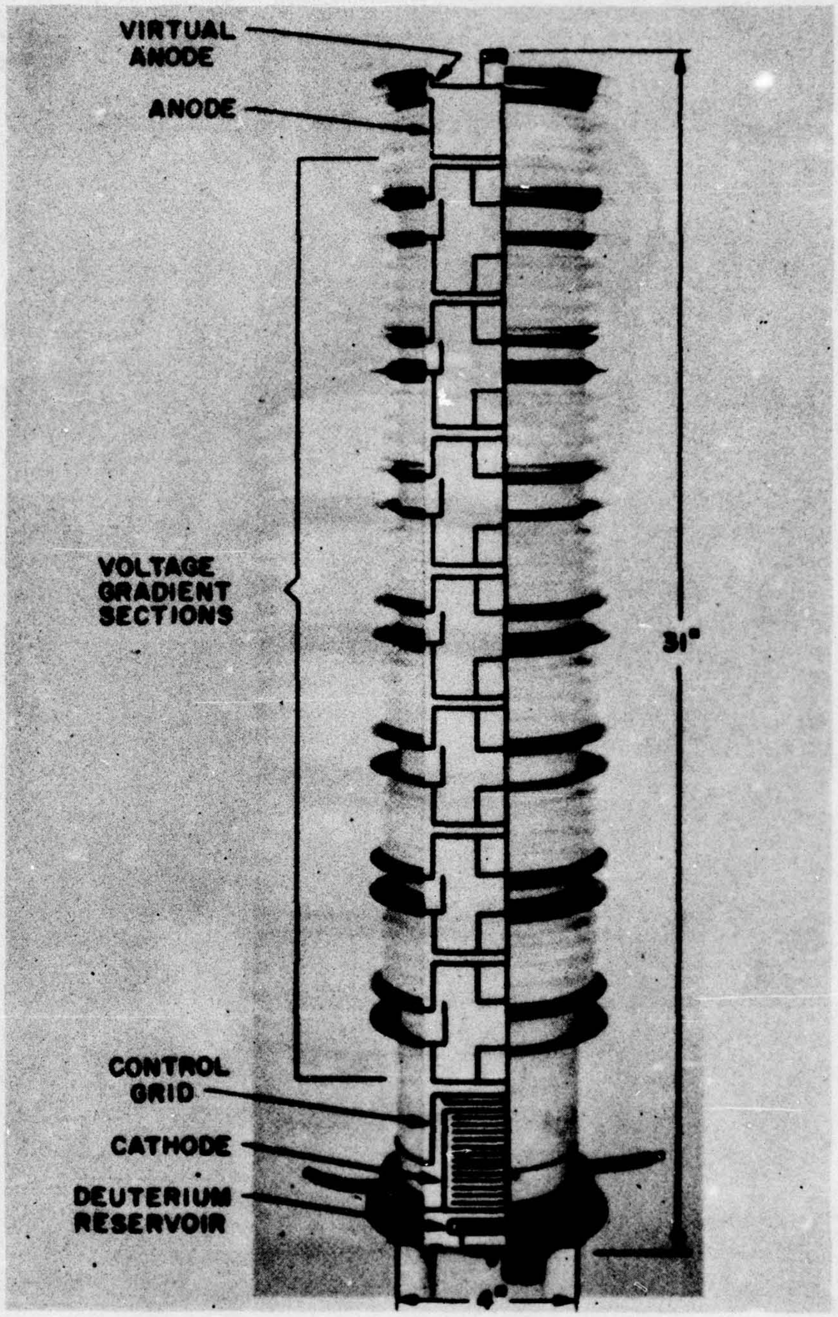


Figure 12, ECOM 250 kv Blumlein Modulator



HIGH VOLTAGE DEUTERIUM THYRATRON
Figure 13

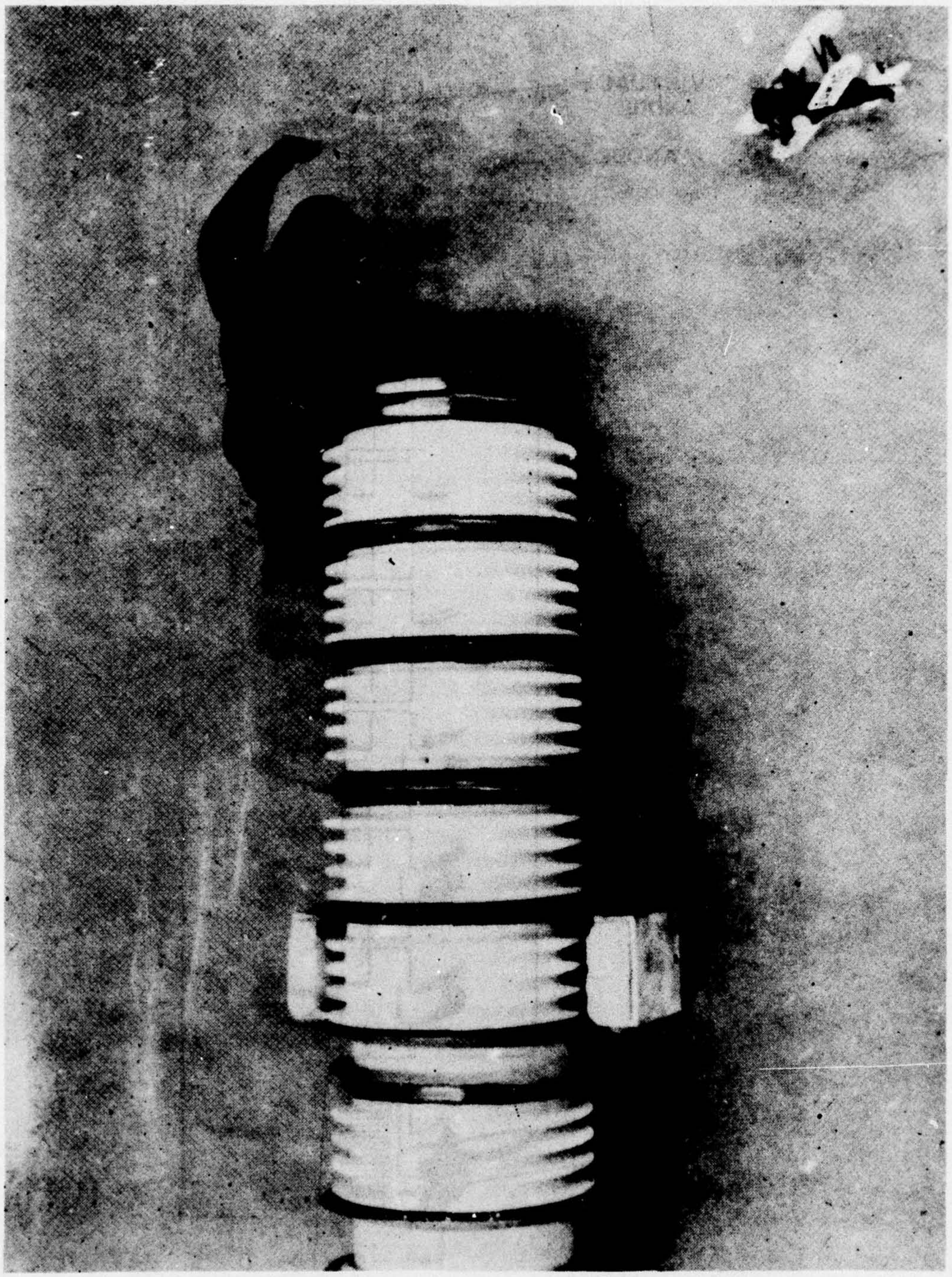


Figure 14, 250 kv Iterative Gap - Cavity Thyration